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# A review of economic approaches modeling the complex interactions between forest management and watershed services

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ABSTRACT

This paper provides a comprehensive review of two decades of published research that applies different economic approaches to address forested watershed management decisions. The review takes stock of the applied integrated economic and ecohydrological modeling approaches and assesses the way these approaches capture the complexities involved when linking ecohydrological and economic systems. The implications of integrating watershed services into forest management decisions are discussed, lessons are drawn from existing approaches and future research needs identified. Existing modeling approaches are categorized from independent modular models with a unidirectional flow of information to fully coupled holistic models, and are analyzed, among others, in terms of the efficiency improvement that forest-based investments achieve in watershed services provision. The review shows that the number of studies investigating the relationship between forest management and watershed services in economic decision-support models is very limited. Only 14 studies that were identified examine these relationships for water supply, while 9 studies were found to focus on the impact on water quality, 2 of which addressed water quality in combination with water supply. A shortcoming is that about half of the studies do not clearly specify baseline conditions to test the incremental value of the evaluated forest management actions in terms of watershed services provision, which undermines evaluating their cost-effectiveness or economic efficiency. A promising finding is nevertheless that in 8 of the 10 studies where these relationships were evaluated in terms of their costs and benefits compared to a specified baseline alternative, forest conservation or forest management is shown to be an economically efficient nature-based solution to supply the watershed services of interest. The limited availability of geo-referenced data and information, including the often complex and confidential nature of cost and price data, and the high data demands of more advanced spatial econometric models are among the main barriers to address relevant forest and water economic interactions. Important future extensions of existing integrated approaches include the further coupling of more detailed ecohydrological models and multi-sectoral hydro-economic models that are able to account for the different risks (floods, droughts, wildfires) and uncertainties under climate change and their impact on watershed services and water security.

## 1. Introduction

Increasing land demand for food and timber production, industrial development and other human needs intensify the pressure on terrestrial and aquatic ecosystems and the watershed services they provide (Easterling and Apps, 2005). The relationship between forests and water resources, in particular, can be characterized as complex, involving synergies and trade-offs between watershed and other ecosystem services that are magnified in rapidly changing environments (Sun and Vose, 2016; Garnier et al., 2015; Ellison et al., 2017). Understanding the effects of forest conditions and management regimes on watershed services is gaining interest worldwide, triggered by climate change, more frequent wildfires and a global water crisis (Hamilton et al., 2008; FAO, 2016; Garcia-Chevesich et al., 2017; Creed and van Noordwijk, 2018).

Watershed services from forests include provisioning services such as the recharge of streams and aquifers for water supply or hydro-power generation, regulating services, such as water purification, erosion and flood control, and cultural services, such as recreational water uses or aesthetic landscape amenities (Ojea et al., 2012; Haines-Young and

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Potschin, 2013). Watersheds also deliver indirect supporting services, such as the maintenance of riparian communities and wetland habitats that generate a number of benefits (Brauman et al., 2007). Forest-water interaction are however complex, and not all aspects of foresed land cover are positive for any issue related to water. For example, at smaller scale a forest may use more water than other vegetations (Filoso et al., 2017). Hence, the scale of the analysis seems to matter, as large-scale deforestation may decrease total downstream water supply (Nordblom et al., 2012).

Although our scientific knowledge and understanding of the functional relationships between the ecological and hydrological processes affecting watershed structure and services have progressed substantially over the last decades, these relationships are still surrounded by many uncertainties and there still is much to learn about the ways ecohydrological and socioeconomic processes can be integrated into forest and water resources management and planning strategies (Hamilton et al., 2008; Ford et al., 2011; Vose et al., 2011; Garnier et al., 2015; Creed et al., 2016; Filoso et al., 2017; Creed and van Noordwijk, 2018).

Many, if not most, payments for watershed services involve management of forest land, including forest conservation and afforestation (Calder, 2007; Brouwer et al., 2011; Martin-Ortega et al., 2015). Payments for forest ecosystem services are often related to carbon sequestration, sometimes in combination with biodiversity conservation as a co-benefit (Wunder et al., 2018; Ezzine-de Blas et al., 2016; Grieg-Gran et al., 2005). A common policy framework for these payments is the United Nations Programme on Reducing Emissions from Deforestation and Forest Degradation (REDD), which has focused primarily on the role of forests as a carbon sink and in carbon sequestration. The avoidance of deforestation has major potential as a means of tackling global climate change (IPCC, 2000; Nabuurs et al., 2007). Deforestation can be avoided at relatively modest cost compared with alternative carbon emission abatement measures in other economic sectors, as demonstrated in various reviews of the economic costs involved (e.g., Phan et al., 2014).

The evidence regarding the cost-effectiveness of forest-based payments as an instrument to enhance watershed services is less obvious compared to payments for carbon sequestration. Often these water-related payment schemes lack appropriate monitoring of quantitative objectives and outcomes supporting their environmental performance (Brouwer et al., 2011; Naeem et al., 2015). This gap in knowledge and information reflects, in part, the fragmented understanding of the complexity underlying ecohydrological processes in forest ecosystems due to the relatively large number of driving factors at multiple scales (Song et al., 2015; Sun et al., 2015). These shortcomings are especially relevant for large-scale ecosystem processes that are sensitive to climatic variations (Vose et al., 2011). In addition, scientific findings related to ecohydrological processes have not always reached the policy domain (Calder, 2007).

Most studies addressing the role of forest watershed management in the provision of water-based services consider an ecohydrological perspective (see Vose et al., 2011, for a review). These studies focus, in particular, on the causal relationships between changes in watershed management and the quantity and quality of water resources, with no or only a very limited analysis of the associated socio-economic drivers and implications. Efforts for integrating forest management and watershed services into economic decision frameworks can be traced back to the 1970's (Worley and Patric, 1971; Calish et al., 1978; Krutilla et al., 1983). However, most of these early economic studies oversimplify forest and water interactions. The number of studies that fully integrate forest management and hydrological variables into an economic valuation and decision-making framework is limited. Accordingly, few of these models would qualify as integrated hydro-economic modeling approaches, i.e. decision-support tools aimed at informing efficient and sustainable water resources management in a way that balances economic and environmental water demands (Brouwer and Hofkes, 2008).

The economic analysis of land use and water interactions has typically focused on agriculture and irrigation water use as the largest water consumer in the world (Harou et al., 2009). Similarly, attention is paid in the literature to the economic effects of agricultural practices on groundwater and surface water quality (e.g. Pannell, 2017; Guan and Hubacek, 2008). Farming activities, both growing crops and livestock breading, are a major source of nitrogen, phosphorus, pesticides, soil sediments, and pathogen pollution of water (Parris, 2011). Forests are not irrigated, but they can reduce blue water yields due to higher evapotranspiration levels (Filoso et al., 2017; Creed and van Noordwijk, 2018), while forest cover is associated with better water quality and lower water treatment costs (Price and Heberling, 2018). Compared to agricultural water use, forest investments (e.g., afforestation) usually have a different time horizon (medium to long-term) involving different levels of uncertainty. As a result, assessing the impact of forestry on water resources requires hydro-economic models that are able to account for specific forest sector characteristics, in particular longer-term time scales and time dependent benefits and costs associated with forest interventions.

This paper reviews existing published studies, carried out worldwide over the last two decades that applied different economic approaches to analyze the effect of forest management decisions on the provision of watershed services. This literature covers a wide range of watershed services such as water purification, groundwater and surface water flow regulation and in-stream and off-stream consumptive uses of water services. The review aims to take stock of progress in both ecohydrological and hydro-economic domains and to examine how the costs and benefits of forest and water resources management are integrated into economic evaluation frameworks, considering the strengths and weaknesses of the models and methods used. The review pays special attention to synergies and trade-offs between forest management and watershed services, their spatial scale, and the treatment of the risks and uncertainties surrounding ecohydrological processes and their relationship with economic activities. In doing so, the paper tries to answer the following three questions: (1) How do the approaches used to analyze the effects of forest management, including conservation, on the provision of watershed services capture the complexity of forest and water interactions? (2) How do these approaches assess watershed services demand and integrate its associated economic value into the economic decision support models? (3) How do these economic values support forest conservation and/or management as a 'green' policy alternative to enhance the provision of watershed services? Based on this review, we draw lessons from the existing approaches and identify future research needs to better inform and articulate sustainable forest and water resources management strategies in watersheds around the world.

## 2. Materials and methods

### 2.1. Study selection

Studies were selected using the Scopus search engine and the following key words: "forest", "management", "hydrology", "water", "watershed service" and "economic", within the article title, abstract and key-words. We limited the search to published journal and conference papers in English, excluding books and grey literature. This search resulted in 1108 papers (December 2017). The abstracts of these papers were screened to check if the studies focus on the integration of forestry, hydrology and economic domains to analyze the interactions between forest management or forest conservation and the provision of watershed services. This led to a reduced database of 75 papers, published between 1961 and 2017. The complete content (methodology, results, discussion and conclusions) of these 75 papers was further screened to assess their relevance for our research objective. This second review round resulted in the final selection of 22 papers

**Table 1**
General description of the selected studies (1).

| N | Type | Reference | Description | Watershed service Source | Watershed service Type | Country/Region | Spatial level | Area (ha) | Integration level |
|---|---|---|---|---|---|---|---|---|---|
| 1 | C | Abildtrup et al. (2013) | Effect of forest cover on the cost of drinking water supply | GW | DWQ | Vosges (FR) | Municipality | 587,400 | UEM |
| 2 | C | Abildtrup and Strange (2000) | Effect of the conversion of natural forest to intensive plantations on ground water treatment costs | GW | DWQ | Denmark | Municipality | nd | UEM |
| 3 | C | Arias et al. (2011) | Effect of forest conservation on hydropower revenues | SW | HP,SC | Cambodia | Watershed | 111,000 | IM |
| 4 | M | Duncker et al. (2012) | Effect of forest management alternatives on water supply and nitrogen deposition | SW | WS, WQ, ND | Germany | Region | nd | IM |
| 5 | M | Eriksson et al. (2011) | Economic implications of the water quality requi rement of the EU WFD on forest management and revenues | SW | eW,WQ ND | Sweden | Sub catchment | nd | IM |
| 6 | C | Fan et al. (2016) | Effect of changes in the forest cover and climate change on the provision of different ES | GW SW | WS, WQ, SC | Japan | Watershed | 290,800 | IM |
| 7 | C | Fiquepron et al. (2013) | Impact of the forest land uses on the costs of drinking water supply | GW SW | DWQ | France | Administrative department | – | UEM |
| 8 | M | Garcia-Prats et al. (2016) | Defining the schedule of silvicultural interventions that maximizes total aggregated net revenues at the study area | GW | WS | Valencia (Spain) | Forest management unit | nd | IM |
| 9 | M | Hosking and Du Preez (1999) | Effects of eliminating invasive alien forest species on water availability | SW | WS | South Africa | Catchment | 29,600 | IM |
| 10 | M | Keles and Baskent (2011) | Economic effect of forest management policy constrains on timber production and water supply | SW | WS | Turkey | Forest mana- | nd | IM |
| 11 | C | Kramer et al. (1997) | Effect of reducing deforestation n the alleviation o of flood damages | SW | FC | Madagascar | Watershed | 26,787 | IM |
| 12 | M | Kucuker and Baskent (2015) | Effects of forest management strategies on carbon seques tration, water and timber yields and economic values | SW | WS | Turkey | Forest unit | 6752 | IM |
| 13 | M | Lauren et al. (2007) | Effects of forest clear-cutting in buffer zones on downstream nitrogen load and forest owners revenues | SW | eW,WQ | Finland | Catchment | 56 | IM |
| 14 | M | McCarthy and Lindenmayer (2007) | Effect of fires and revegetation with native and exotic forest species on WS | SW | WS | Australia | Capital territory | 235,800 | IM |
| 15 | M | Nordblom et al. (2010) | Effect of land use decisions on soil salinity reduction and water supply | SW SW | SSC, WS | Australia | Catchment | 64,000 | LC |
| 16 | M | Nordblom et al. (2012) | Effect of large tree plantation on downstream water supply and economic losses for irrigation and domestic uses | GW SW | WS,eW WQ | Australia | Basin | 2.8 million | IM |
| 17 | M | Ovando et al.(2017) | Effect of forest management and abandonment on water yield | SW | WS | Andalusia (Spain) | Farm | 297,500 | LC |
| 18 | C | Quintero, et al.(2009) | Efficient PES design for agroforestry and forest conservation actions | GW SW | SC, WS | Peru Ecuador | Watershed | 730 1317 | IM |
| 19 | M | Simonit et al.(2015) | The impact of forest thinning on managing water supply reliability and costs | GW SW | SC,WS | Arizona (USA) | River basin | nd | LC |
| 20 | M | Susaeta et al. (2016) | Effect of integration of payments for water supply on forest profitability and optimal management | SW | WS | Florida (USA) | Region | nd | IM |
| 21 | M | Susaeta et al. (2017) | Impacts of climate change and forest management on water supply | SW | WS | Southern USA | Region | 100,000 | IM |
| 22 | C | Vincent et al.(2016) | The effect of tropical forest (virgin and managed) conservation on water treatment costs | GW SW | WQ | Malaysia | Catchment areas | 6 million | UEM |

Notes: (1) The type refers to the group of studies, being C: forest conservation (including avoided deforestation) and M: forest management (including afforestation/reforestation). The (watershed) service's abbreviations are referred to: DW: drinking water; eW: water environmental flow (e-flow); FC: flood control; GW: ground water; HP: hydro-power; ND: nutrients deposition; Q for quality regulation; S for supply; SSR: soil salinity reduction; SC: sediment control. Other abbreviations include: ES: ecosystem serviceS; EU WFD: European Union Water Framework Directive's; nd: not defined; PES: payments for ES. The abbreviations for the integration of ecohydrological and economic models (systems) indicate: IM: independent model; LC loosely coupled model; UEM: single economic model.

published between 1997 and 2017 that match our selection criteria (English articles linking forestry and hydrology in environmental-economic evaluation and optimization frameworks), and research interest in integrated environmental-economic modeling of forest and watershed services (Table 1). This selection excludes studies focused on the economic valuation of watershed and other forest ecosystem services only, which are reviewed already elsewhere (Lele, 2009; Ojea et al., 2012). Instead, the review presented here focuses on studies that explicitly integrate ecohydrological and economic assessments (methods and models) in a broader environmental-economic evaluation and decision-support framework.

### 2.2. Assessment and classification of studies

The integration of ecohydrological and economic models and methods for assessing the environmental and economic performance of forest resources management and the provision of watershed services requires scientific knowledge and expertise from different research fields. Those fields include forestry, hydrology, and economics, which can be handled as independent models, as more integrated, but loosely-coupled modular approaches, or fully-coupled holistic modeling frameworks allowing for dynamic feedback loops between natural and economic systems (Brouwer and Hofkes, 2008). Those models can be developed as simple single sector models based on economic estimations of demand (consumption) and supply (production) of the forest and water related services involved, or more complex economic optimization procedures involving a set of simultaneous equations considering the inter-linkages between multiple water-dependent economic sectors (Fig. 1).

We use the term ecohydrology here and after to refer to forest ecology and hydrological models. The existing ecohydrological and economic models and methods address and reflect different levels of complexity, which are defined here in terms of non-linearities in causal relationships and feedback loops that change systems of multiple interacting components. We are particularly interested in examining how comprehensive these models and methods are in their ability to capture complexity, both in their specific field and jointly to connect one field to the other. Complexity levels in this study are assessed in qualitative terms as low, medium and high, and these classifications are assigned to studies following the criteria summarized in Table 2.

Different classification criteria are considered to identify the type of forest, hydrological and economic models, while each one of these models are evaluated considering similar criteria regarding the specific characteristics of the modeling frameworks. The complexity of the interactions between the ecohydrological and economic systems that is captured by a specific modeling approach depends, among others, on the comprehensiveness and the level of detail of the information used in the analysis, the model solving technique, and the level of integration. In order to be able to assess the complexity of these interactions, it is important to understand the characteristics of the different components making up the interactions, in particular existing modeling approaches and methods in forestry, hydrology and economics. Additionally, we examine how these integrated modeling approaches account for the relevant spatial scales and any risk and uncertainty involved.

Hydrological and forestry modeling approaches have a number of similarities. Both can be based on relatively simple empirical relationships or on more complex models based on a combination of empirical mechanisms and conceptual or theoretical understanding of relevant ecological and physical processes and interactions. Most prevalent forest models are empirical growth and yield models, describing growth in terms of diameter increment, and typically portraying mono-specific and even-aged stands as those found in plantations (Twery, 2004), and to a lesser extent mixed uneven-aged forest stands (Porté and Bartelink, 2002). Empirical growth and yield models struggle to capture tree growth responses to disturbances, as those are often beyond the capacity of field observations (He, 2008). Empirical hydrological models typically describe water balances, analyzing concurrent inflow and outflow time series, without necessarily considering the features and processes of the wider hydrological system. The validity of these models may therefore be restricted to the boundaries of the analyzed domain

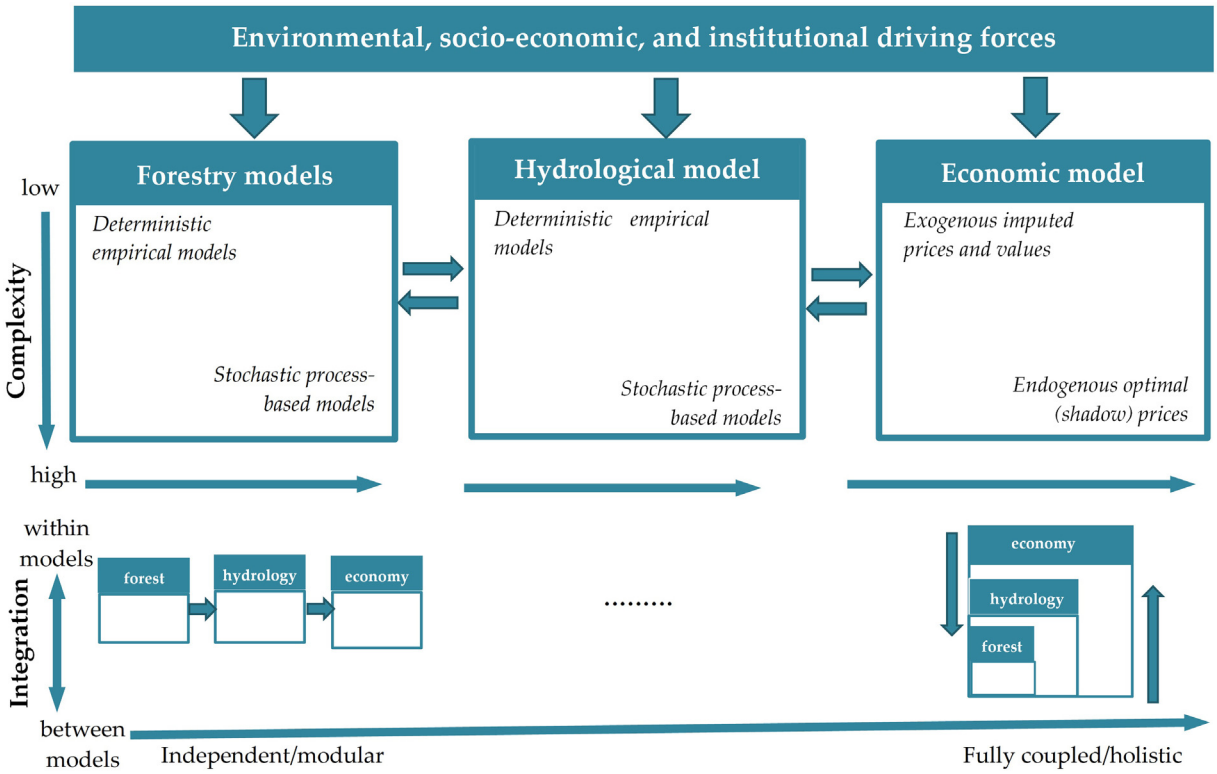


**Fig. 1.** Disciplinary dimensions and integration level underlying forest hydro-economic models.

**Table 2**
Classification and examples of different types of models across different levels of complexity.

| | Complexity | | |
|---|---|---|---|
| | Low | Medium | High |
| Model type | | | |
| Forest models | Empirical models for single and mixed forest species | Process-based models applied at individual tree or forest stand level | Process-based models applied at the forest landscape level |
| Hydrological model | Empirical water model | Physically-based (semi-distributed) model | Physically-based (spatially) distributed model |
| Economic models | Imputed value model | Economic model with exogenous prices | Economic model with endogenous (shadow) prices |
| Model characteristics | | | |
| Optimization techniques | No optimization techniques applied (Simulation models) | Linear optimization techniques | Non-linear optimization techniques |
| Uncertainty assessment | No – deterministic of results to specific variables | Yes - sensitivity analysis in models | Yes - stochastic processes |
| Spatial scale | No spatial differentiation | Spatial differentiation | Spatial correlation |
| Integration of forest, hydrological and economic models | Independent eco-hydrology and economic models | Loosely coupled ecohydrological and economic models (modular approach) | Fully coupled ecohydrological and economic models (holistic approach) |

(Refsgaard, 1996; Devi et al., 2015).

A second type of forest growth models is a more process-based approach that includes assumed or observed mechanisms of growth, competition and mortality, along with theoretically expected controlling factors, such as available light, nutrients, temperature, water, and their interactions (Twery, 2004; He, 2008). These models can be either applied at the individual tree or stand level. Physically based lumped (semi-distributed) hydrological models are conceptual hydrological approaches that also include empirical equations, representing the wider catchment theoretically as, for example, a series of cascading stores of water, in which they are recharged by rainfall and infiltration, and are emptied by evaporation, runoff and drainage (Mulligan, 2004).

The third type of forest landscape models represents, from a theoretical perspective, the vegetation and ecosystem responses to interactions of spatial patterns and ecological processes at different spatio-temporal scales and under different disturbances and equilibrium conditions (He, 2008). Large data requirements, and the fact that many of the interactions are fairly descriptive, have limited the practical application of process-based models at the scale of individual trees, stands or forest landscapes as management tools (Porté and Bartelink, 2002). Based on physical principles, the third category of hydrological models has also been referred to as a physically-based (spatially) distributed process models, comprising mathematical representations of hydrological processes in a catchment area (Devi et al., 2015). Spatially distributed physically-based hydrological models are used on the assumption that spatially differentiated physical systems are more realistic than lumped ones (Refsgaard, 1996; Mulligan, 2004).

Economic models and methods are characterized based on other dimensions than ecohydrological models, but their complexity and comprehensiveness is, in principle, based on similar considerations. That is, the extent to which different components of the economic system and their interactions are captured and modeled in the analysis. Typically, an important difference between ecohydrological and economic models is that the latter apply optimization procedures to assess the optimal levels of input and output, given a set of physical or management constrains, while the former are usually based on simulation procedures (Brouwer and Hofkes, 2008; Harou et al., 2009). In this paper we consider three main types of economic modeling approaches that represent different levels of complexity in capturing forest and water economic interactions. We label the most simple economic approach as the imputed value model, comprising models that apply average market and cost prices to biophysical effects (e.g. hydro-power or timber production), involving no economic optimization, and where the assessment of costs and effects is based on the transfer of unit (cost) prices. More complex economic models involve optimization, which entails finding the alternatives that have the highest achievable performance or are the most cost-effective. Economic optimization can be based on maximization of the net benefits, encompassing the comparison of monetized market and non-market inputs and outputs in a cost-benefit analysis framework, or, alternatively, on the minimization of the costs, involving a comparison of the relative costs of an intervention with its non-monetary impact, in a cost-effectiveness analysis framework.

The complexity level in economic optimization models depends to a large extent on whether prices are given, or they are estimated or simulated within the model as market equilibrium (shadow) prices. A single economic sector model represents partial equilibrium conditions, meaning that market prices are given (exogenous) and changes in baseline conditions, for example due to a policy intervention (e.g. taxes on water) or an external shock (e.g. climate change), do not affect general price levels in relevant markets, only the amount of a good produced or consumed. Single sector models combine empirical relationships between two or more variables under theoretical assumptions related to the behavior of consumers and producers for estimating demand (consumption) and supply (production) functions.

These individual sectors typically do not operate in isolation and larger scale policy interventions in one sector may have consequences for other sectors, and eventually affect the economy as a whole. These so called multiplier effects are captured in more holistic general equilibrium models, describing the interactions that exist between different sectors of the economy, where price levels in input and output markets may also change as a result of changes in demand and supply instead of being given. Examples of such multiplier effects are the impact of a change in primary agricultural production on the food industry or a change in the primary forestry sector on the timber dependent construction industry. Those effects are captured in more holistic general equilibrium models, describing the interactions that exist between different sectors of the economy, where price levels in input and output markets may also change as a result of changes in demand and supply instead of being given.

Economic analysis can be based on actual results of specific actions and production levels *ex-post*, or *ex-ante* based on forecasted outcomes of possible courses of action. An example of such an *ex-post* analysis is the econometric modeling of the effect of past or current forest management practices or forest conservation on the provision costs of watershed services. Econometric models are usually used to capture empirical relationships between two or more variables, for example production functions (similar to yield functions) describing the amount of water input (and associated costs) needed to irrigate agricultural land to produce 1 kg of output (and associated revenues). Usually these inputs and outputs are described in monetary terms. *Ex-ante* economic evaluation relies on assumptions with regards to the theoretically

expected behavior of economic agents. Examples include landowners aiming to maximize their profit from different types of land uses or water utility managers aiming at minimizing operating and capital costs at which a watershed service is provided.

Ecohydrological and economic models can be developed and operated independently of each other in a unidirectional way, where the outcome of one component, e.g. the forest model or data, is used by another component, e.g. the hydrological or the economic model. This approach does not involve feedback loops between the forest, hydrological and economic components of the system, and is generally considered to reflect a low level of integration and complexity. Ecohydrological and economic models may also be more connected, considering different degrees of coupling. Loosely coupled models refer here to models which aim at further interconnecting the components of a system or network, in which the separate components depend on each other to the least extent feasible. An example is a coupled forestry-hydrology model, where changes in the forest management regime affects water flows or water quality downstream through the integration of spatially differentiated land-water runoff functions. Such a model operation is an example of loose coupling and categorized, in this review, as reflecting a medium level of complexity. Fully coupled models are defined as an interactive system of simultaneous equations that allow for feedbacks loops among the various economic and ecohydrological components. An example of such a fully coupled model would be an economic optimization procedure based on the joint modeling of timber revenues and watershed service values, where changes in the marginal economic costs and benefits result in feedbacks to further modify the forestry management and water balance models, e.g. by selecting alternative forest thinning strategies. This latter type of models would represent here the highest level of complexity.

## 3. Results

### 3.1. General overview of studies

The economic evaluation of forest and water interactions is gaining growing interest in the academic and policy arena. Three quarters of the selected studies in our review have been published in the last five years, and most of selected studies (91%) after 1999. The attention paid to economic decision support models involving the management of forest and water resources in watersheds is expected to further increase in the coming years, in view of international initiatives such as the UNECE Water Convention, the Ministerial Conference on the Protection of Forests in Europe (MCPFE, 2009), and the FAO Forest and Water program, the implementation of which started in 2015, and is aimed at addressing forest-water interactions in science, policy, economics and forest practice (FAO, 2016).

This review covers a heterogeneous set of studies, in terms of their location, spatial scale, the water and forest resources management contexts and the ecohydrological, and economic methodological approaches used. Fig. 2 shows the locations of the selected studies. Ten of 22 studies are located in Europe (Denmark, Finland, France, Germany, Spain, Sweden, Turkey), three in Asia (Cambodia, Japan, Malaysia), three in the US (Arizona, South Carolina, Georgia and Florida), one in South America (Peru and Ecuador), three in Australia, and two in Africa (Madagascar and South Africa). The watersheds involved cover tropical, temperate, boreal and Mediterranean forests.

The selected studies address either the effect of forest resources conservation (36%) or forest management (64%) on the provision of different watershed services. Fourteen out of the 22 selected studies examine the effect of forest cover and forest management regimes on surface and/or ground water supply, while nine studies consider water quality regulation and six the regulation of sediment loading and deposition, floods, and soil salinity. Most studies (82%) focus on consumptive water uses for agriculture, drinking water supply, and industrial uses, while three studies consider environmental water flows (e-flows) required to sustain freshwater ecosystems, and one on energy (hydro-power) production. Four studies evaluate the simultaneous provision of two or more watershed services, such as water supply and water quality regulation or water supply and sediments or soil salinity control, allowing for the analysis of potential trade-offs or synergies between those services (Table 1). Cultural services do not receive much attention in the selected studies, as also reported in Ojea et al. (2012).

The geographical units and their area size vary considerably, with studies focusing on small and large catchments, river basins, municipalities, regions and even an entire country (Table 1). Tables A.1 and A.2.1 to A.2.3 in the supplementary materials provide a more detailed description of the models, methods and other characteristics of the surveyed studies, considering the classification criteria presented in Table 2 and Section 2. The next sections describe and analyze commonalities and differences among the studies in terms of the methods used to model, evaluate and integrate forest and water interactions in economic evaluations.

### 3.2. Coupled forest and hydrological modeling

Although forest revenues play a major role in the analyzed decision-making frameworks, most of the studies apply relatively simple forest growth and yield models or only consider secondary data on forest cover and other land uses distribution. Those studies use deterministic individual tree or stand based yield tables that present the expected growth and yield patterns from particular management prescriptions in the study areas (e.g., Keles and Baskent, 2011; Kucuker and Baskent, 2015; Ovando et al., 2017; Susaeta et al., 2016). Yield tables usually describe mono-specific and even-aged stands, and forest growth and yield functions. Duncker et al. (2012) apply a more sophisticated approach, consisting of a process-based model that combines tree and stand-based growth models using recursive procedures that allow for feedbacks between the individual trees and the stand growth functions.

In contrast, more than 40% of the studies use physically-based hydrological models to quantify the effect of forest management or forest conservation on the provision of a single or multiple watershed services. Physically-based hydrological models are used to simulate either spatially distributed surface run-off, ground water recharge and sediments loads (Arias et al., 2011; Fan et al., 2016; Ovando et al., 2017; Quintero et al., 2009; Simonit et al., 2015), or to estimate lumped water balance figures (Duncker et al., 2012; Garcia-Prats et al., 2016; Nordblom et al., 2010). Other studies use a set of conceptual or empirically calibrated hydrological functions to represent both hydrological and sedimentation processes. The parameters of these functions are either taken from existing literature (Eriksson et al., 2011; Nordblom et al., 2012; Susaeta et al., 2017) or quantified using primary data collected in the case study area (Kramer et al., 1997; Simonit et al., 2015).

A smaller group of contributions combine forest and hydrological variables to simulate their responses to changes in land use or forest management regimes. Lauren et al. (2007) apply a process-based ecological model to simulate tree physiological and ecosystem responses to changes in thinning intensity, and their effect on water quality. Susaeta et al. (2017) use a physiological process-based model to predict forest growth and yield under different climate scenarios, evaluating the response of forest growth to changes in precipitation levels. The model used by Nordblom et al. (2010) analyses hydrological and land use interactions employing an empirical global model that relates water yield to land uses and rainfall. Nordblom et al. (2012) use the same global land-use and water yield curves, along with a set of assumptions to connect increments in tree volume and water consumption to annual rainfall. Susaeta et al. (2016) model changes in water yield depending on variations in the forest leaf area index (LAI), which is a function of forest management variables, such as the stand density and productivity. Similarly, Keles ad Baskent (2011) and Kucuker and Baskent (2015) relate changes in surface water levels to changes in forest basal

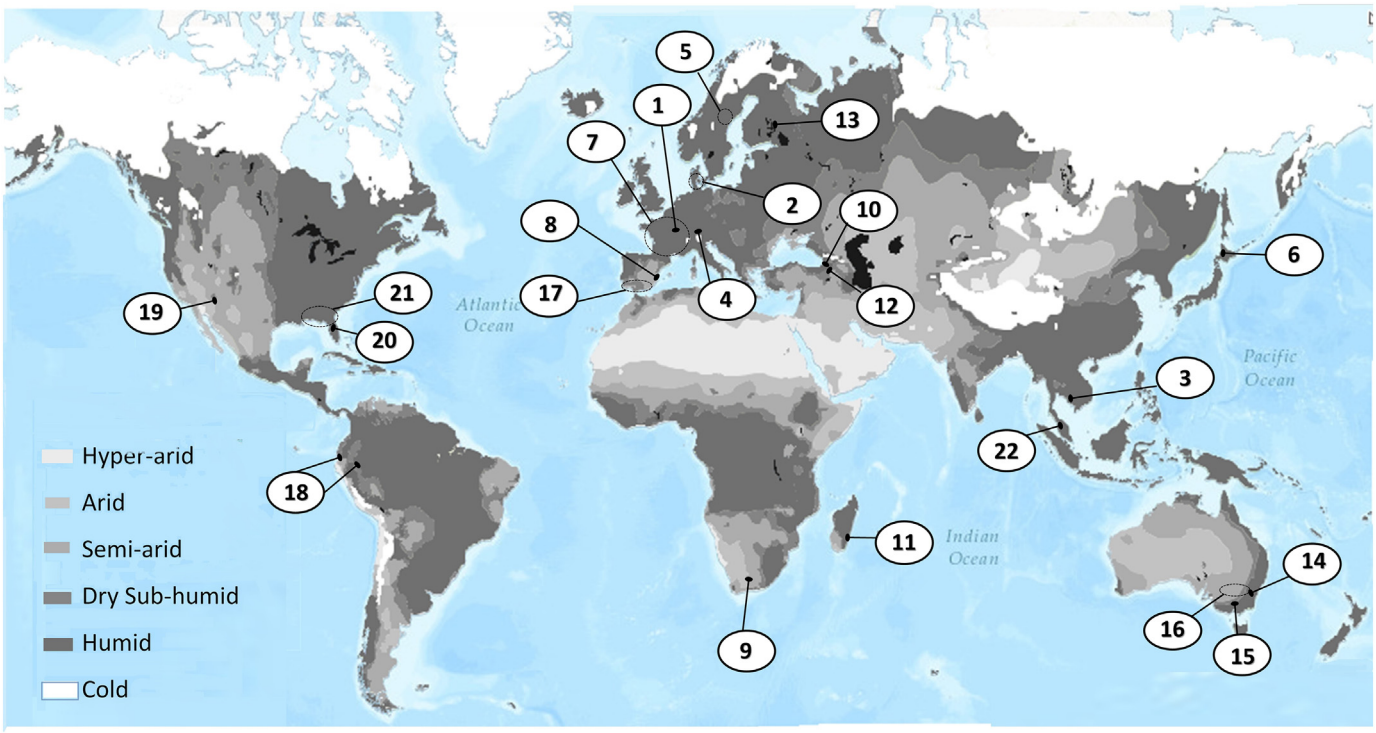


**Fig. 2.** Geographical distribution of studies.

area using empirical relationships based on primary data collected in their study regions.

The impacts of changes in forest management typically manifest themselves over longer periods of time, and as a result most of the studies simulate forest evolution and associated timber and watershed yields in the long-term. However, only a small number of studies examine the response of forest growth and hydrological responses to changes in key climatic variables (Kramer et al., 1997; Arias et al., 2011; Fan et al., 2016; Garcia-Prats et al., 2016; Susaeta et al., 2017). A few studies specifically include precipitation as a variable of forest and water interactions (Nordblom et al., 2012; Vincent et al., 2016), which allow the models to evaluate the potential effect of changes in precipitation patterns due to climate change on the provision of watershed services. Finally, most modeling approaches do not fully integrate the interactions between forests and hydrological variables, such as the effect of drought on tree growth and mortality, or only offer a loose and, most of the time, deterministic unidirectional coupling of relevant variables, even though these interactions are expected to be driven by more complex and uncertain processes (Bryan et al., 2013). The effect of drought on tree growth responses can be relevant in particular in arid areas (Vanoni et al., 2016).

### 3.3. Environmental-economic evaluation of forest and water services

Economic models with exogenous prices, based (mainly) on net benefit maximization (cost-benefit analysis: 68%) or cost minimization (cost-effec-tiveness analysis: 14%) are the main economic evaluation techniques applied in the studies included in this review. The type of economic valuation methods considered for the estimation of the costs and/or benefit functions associated to watershed services provision are rather heterogeneous. Cost-based methods, such as production costs, avoided damage costs, and opportunity costs, and market pricing are the most frequently applied economic valuation approaches in 64% and 9% of the selected studies, respectively. Other studies focus mainly or on biophysical values for watershed services, where the economic analysis and decisions are based on market prices for timber and other market revenues from changing land use or management regimes (Lauren et al., 2007; Quintero et al., 2009; Nordblom et al., 2010; Eriksson et al., 2011; Arias et al., 2011; Duncker et al., 2012; Fan et al., 2016).

The production and treatment costs of water supply are used in three econometric studies surveyed, as proxy values for the water purification service (Abildtrup et al., 2013; Fiquepron et al., 2013; Vincent et al., 2016). Similarly, the value of the service groundwater recharge is assessed by considering the groundwater pumping expenditures as production costs (Simonit et al., 2015; Susaeta et al., 2016, 2017). The avoided damage cost method is applied to price services such as sediment retention and flood control services, in cases where hydro-power reservoirs get congested as a result of deforestation-related sedimentation, reducing the life-time of the reservoirs (Arias et al., 2011), or deforestation increases the risk of flood damage for farmers (Kramer et al., 1997). The price of water supply charged by water utilities to consumers is also used, in some cases, as a proxy for the value of water provisioning services (surface and groundwater). Not in all studies, however, are all the production costs of this service accounted for (Hosking and Du Preez, 1999; Abildtrup and Strange, 2000) or only share of the existing water price is used after subtracting the unit production costs of the water utilities involved (McCarthy and Lindenmayer, 2007; Keles and Baskent, 2011; Kucuker and Baskent, 2015; Simonit et al., 2015). In one study the hedonic price method is used to estimate the stock value of blue water by comparing the value of irrigated and non-irrigated lands (Ovando et al., 2017).

The various economic valuation approaches used to price watershed services in the studies reviewed here suffer from different degrees of oversimplifications, and are sometimes based on strong assumptions. This includes assigning the entire water supply price charged to final consumers to the water provisioning services delivered by forest ecosystems, ignoring necessary input factors like capital and labor to supply water, or the fact that water prices charged by water utilities may be underestimated and not cover all costs due to political decision-

making (Pulido-Velazquez et al., 2008). Likewise, cost-based valuation methods do not provide strict economic values, as they do not account for the utility that watershed services have to individuals, which is typically based on social preferences and willingness to pay for the services involved (Mueller et al., 2013).

Ideally, economically meaningful values for the watershed services resulting from forest management interventions would account for the upstream-downstream changes in human well-being (Turner et al., 2004). However, only few studies consider both the upstream and downstream marginal welfare changes due to fluctuations in the provision of the watershed services resulting from forest management or land allocation decisions (Garcia-Prats et al., 2016; Nordblom et al., 2012; Kramer et al., 1997). For example, Garcia-Prats et al. (2016) use the shadow price of water provided by a basin-wide hydro-economic model, while Nordblom et al. (2012) estimate the marginal opportunity value of the water consumed by (upstream) tree plantations, accounting for upstream and downstream water demands and water entitlements held by irrigators and other water users.

### 3.4. Integration of forestry, hydrology and economic decision- support models

The multiple interactions between ecohydrological and economic systems can be complex and often surrounded by many uncertainties due to limited or the lack of knowledge and information. The degree to which forest and hydrological models are connected to economic evaluation and decision-support models to capture those complex interactions varies widely across studies and depends, in part, on how economic behavior is modeled and integrated within existing ecohydrological models, the treatment of uncertainties surrounding control and exogenous variables, and the spatial scales considered in the coupled modeling approaches. Fig. 3 provides an overview of the classification of the various components of the evaluated studies that integrate forestry, hydrology and economic models to capture the interactions and complexities, following the criteria outlined in Table 2.

Most of the surveyed studies rely on simple economic optimization algorithms subject to different forestry and hydrological flow variables. The most simple models estimate the net present value (NPV) of the flow of revenues accruing to a landowner or community due to the sale of timber and water services over a specific time period (Kramer et al., 1997; Hosking and Du Preez, 1999; Arias et al., 2011; Duncker et al., 2012; Lauren et al., 2007; Susaeta et al., 2016, 2017; Ovando et al., 2017). More sophisticated economic models analyze optimal forest investment decisions choosing from a set of land use and forest management alternatives, aimed at (i) the maximization of their net revenues (Eriksson et al., 2011; Kucuker and Baskent, 2015; Keles and Baskent, 2011; Garcia-Prats et al., 2016; Quintero et al., 2009), (ii) the minimization of their costs for achieving specific environmental targets (Fan et al., 2016; Nordblom et al., 2010), or (iii) the maximization of their robustness, where outcomes are less sensitive to the key uncertainties involved (McCarthy and Lindenmayer, 2007). Single objective linear optimization addressing both the physical and management constraints of the system, is the most popular mathematical optimization technique used in the revised here studies. Fan et al. (2016) is an exception, as they use optimization by annealing procedures to achieve specific conservation targets close to the minimum cost.

Forest investments at smaller scale, such as a catchment, are not expected to affect, in a significant way, the regional supply of watershed services or economic demand functions. In those cases, the role of basin-wide hydro-economic models that represent upstream and downstream water demand and supply and their interactions on economic markets clearance seems limited. Economic decision variables rather depend on the economically sound imputation of values for watershed services for comparison with their costs of provision. Larger scale forest projects may have a relevant impact on the downstream supply and upstream demand of water, and potentially on water-related markets and water-dependent sectors. Although, a number of the studies cover large areas (Table 1), only one of them explicitly analyzes the effect of forest interventions on water supply and demand, water prices and their welfare effects on economic sectors competing for water (forestry, agriculture, industry, residence and environment) (Nordblom et al., 2012).

In general, we observe that most of the surveyed models (82%) use both independent or loosely coupled forest and hydrological models providing input data to the economic decision problem (Table 1). There are some exceptions. The forest and hydrological models in Lauren et al. (2007) operate as a fully integrated holistic model, with feedback loops between the hydrological and ecological components to estimate nitrogen transport, hydrological processes above the ground, and above and below ground net photosynthesis. Despite offering a relatively simple representation of forest dynamics, the water balance model in Nordblom et al. (2010) integrates land use (including forest) and hydrological models to simulate the effect of land use changes on salt load and water yields. Likewise, most of the economic models operate as independent units using inputs from the hydrological and/or forest processes without feedback loops between the economic and ecohydrological systems. There are also some exceptions where the forest or hydrological model is coupled to the economic decision support model. The study by Ovando et al. (2017) allows for feedback loops between the economic decision and forest management models, as the forest investment decision (i.e., to harvest timber and to invest in natural forest regeneration treatments) conditions forest evolution, and directly the future provision of carbon sequestration services and forest products, and indirectly the future provision of water. Similarly, Simonit et al. (2015) consider eco-hydrological and economic interactions to simulate the spatial effects of forest thinning on water yield and water supply costs.

The integration of risk and uncertainties into long-term forest management decisions has received widely attention in the forestry literature, for both handling natural hazards and market-based risks (see Hanewinkel et al., 2011, for a review). Nonetheless, most of the surveyed studies (77%) apply deterministic modeling approaches, and address risk and uncertainties either through a scenario analysis (Fan et al., 2016; Susaeta et al., 2017) or a sensitivity analysis of economic factors, such as timber prices or discount rates (Arias et al., 2011; Duncker et al., 2012; Garcia-Prats et al., 2016; Ovando et al., 2017; Quintero et al., 2009; Susaeta et al., 2016), but also of policies, such as specific environmental targets (Eriksson et al., 2011; Nordblom et al., 2010) and of biophysical variables, such as rainfall (Susaeta et al., 2017). A few studies account for the uncertain (or probabilistic) nature of parameters affecting the production functions of forest and watershed goods and services, such as stochastic processes determining groundwater quality and forest market values (Abildtrup and Strange, 2000), or the random occurrence of fires, and their effect on timber and water provisioning values (McCarthy and Lindenmayer, 2007).

Less than half of the models present spatially distributed results, which is rather surprising, since both forest and hydrological processes are spatially dependent, and spatial heterogeneity is expected in studies covering large areas (e.g., Simonit et al., 2015; Ovando et al., 2017). Likewise, most of the studies offer a static picture of the contribution of forests to deliver watershed services, with no or limited evaluation of the dynamic nature of the provision of watershed and forest good and services.

Econometric models implicitly integrate technical, economic and ecological data and processes, but those are not necessarily analyzed explicitly. Although, econometric models hold promise to fine-tuned results by connecting drinking water provision or treatment costs with the specific attributes of the catchment areas, in general, those models have a weak spatial relation to the catchment area, as they mainly focus on administrative divisions.

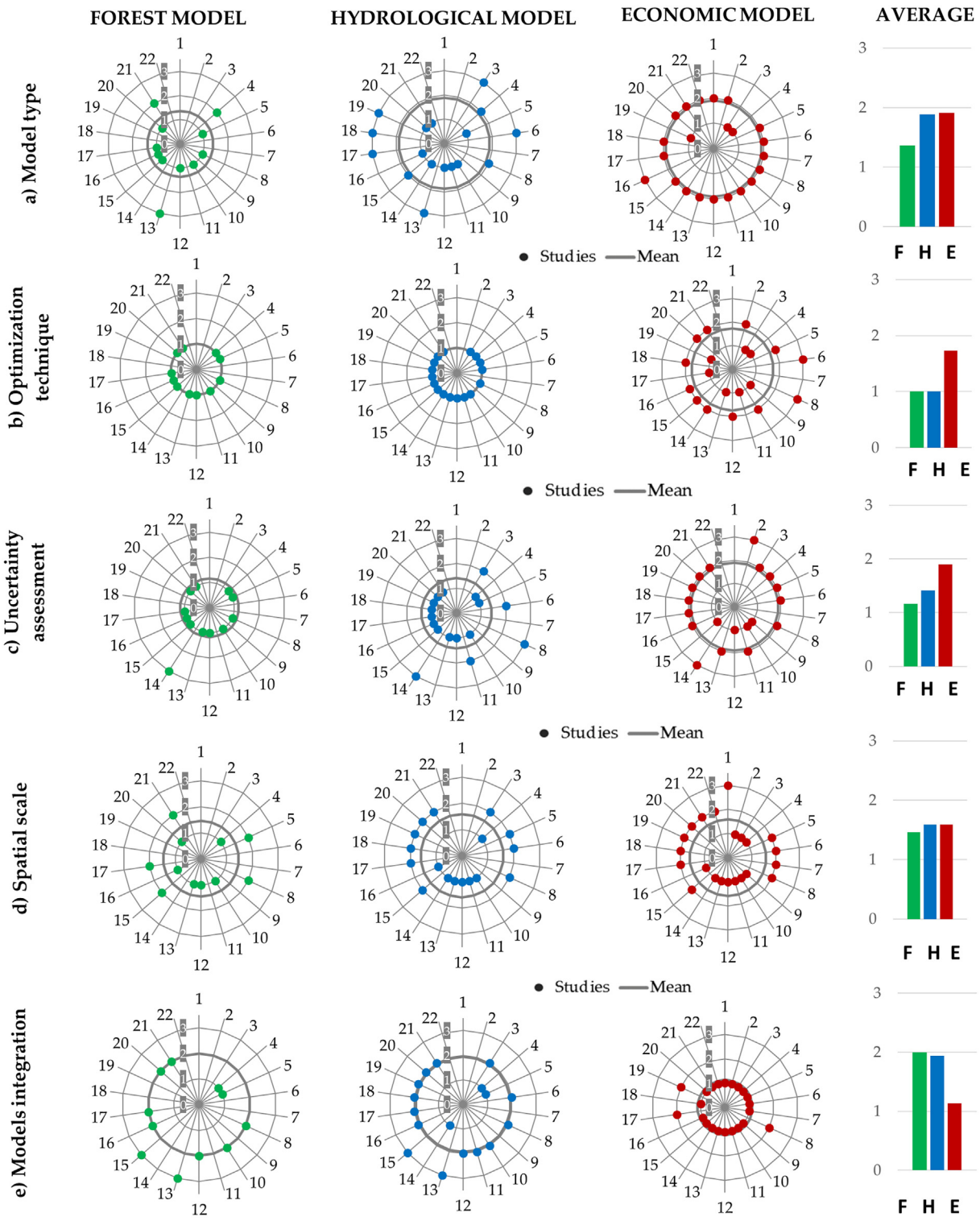


**Fig. 3.** Classification of the selected studies according to the complexity of the approaches and information involved.
Note: the axis indicates the complexity level (1 = low, 2 = medium; 3 = high).

### 3.5. Trade-offs and synergies between forest and watershed services

The number of studies and their geographical representation is limited, impairing the derivation of general lessons regarding the economic interactions of forest-based actions and watershed services. Nevertheless, the sampled studies address a sufficiently broad diversity of water resources to provide insight in the potential trade-offs and synergies between timber and watershed services, and between different watershed services, in particular the effect of forest conservation and management options on water quality and quantity regulation. Fig. 4 summarizes whether or not the studies detect an effect of forest management and conservation on the provision of watershed services, and whether trade-offs exist between timber and water services provision.

About two thirds of the studies (14) analyze the relationship between forest management decisions and water supply, while 9 studies

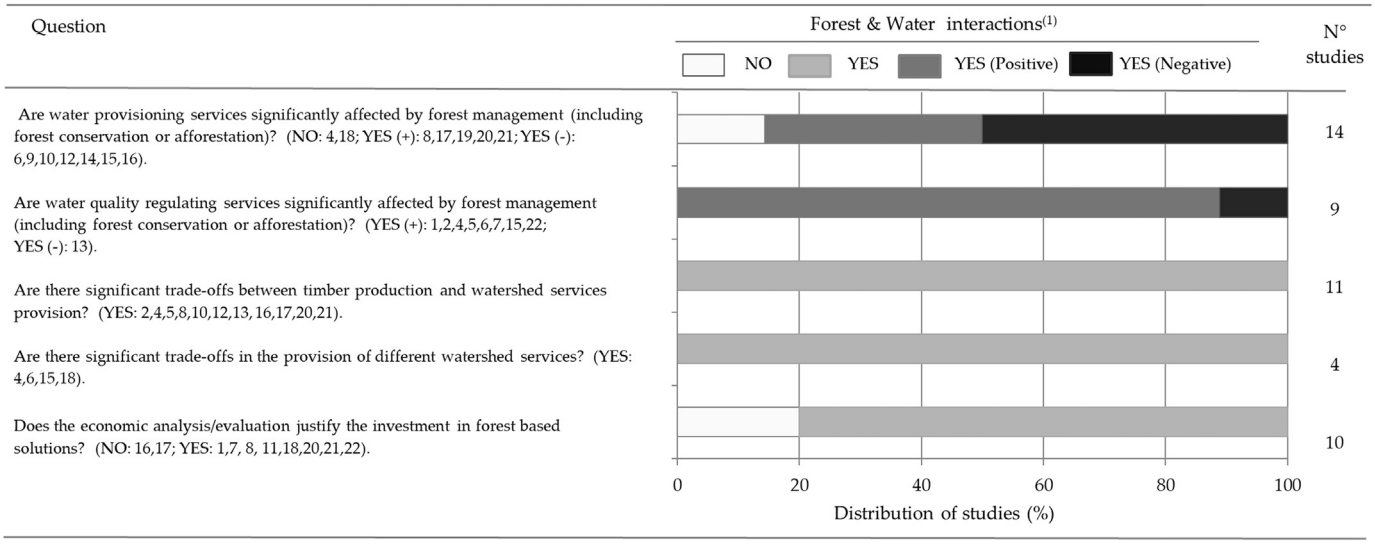
Question
Forest & Water interactions(1)
NO
YES
YES (Positive)
YES (Negative)
N° studies
Are water provisioning services significantly affected by forest management (including forest conservation or afforestation)? (NO: 4,18; YES (+): 8,17,19,20,21; YES (-): 6,9,10,12,14,15,16).
14
Are water quality regulating services significantly affected by forest management (including forest conservation or afforestation)? (YES (+): 1,2,4,5,6,7,15,22; YES (-): 13).
9
Are there significant trade-offs between timber production and watershed services provision? (YES: 2,4,5,8,10,12,13, 16,17,20,21).
11
Are there significant trade-offs in the provision of different watershed services? (YES: 4,6,15,18).
4
Does the economic analysis/evaluation justify the investment in forest based solutions? (NO: 16,17; YES: 1,7, 8, 11,18,20,21,22).
10
0
20
40
60
80
100
Distribution of studies (%)

**Fig. 4.** Effect of forest and water interactions on economic decisions and results.
Notes: (1) Distribution of studies (share (%) of the studies), accounts for the number of studies that address the specific question.

focused on the impact of watershed forest management on water quality, 2 of which addressed both water supply and water quality (see Fig.4). In 12 of the 14 studies a significant relationship was detected for water supply services, but this relationship was only positive in 36% of the cases. The former results are in line with the comprehensive review conducted by Filoso et al. (2017), that suggests that forest cover restoration is likely to reduce water yields, at least in the short term and in small catchments. On the other hand, thinning treatments are expected to favor water supply (Garcia-Prats et al., 2016; Simonit et al., 2015; Ovando et al., 2017). However, the studies that analyze this specific forestry strategy do not further analyze the effects of more intense forest management regimes on the quality of ground or surface water, wich could be relevant (Eriksson et al., 2011). In our review, water quality is improved in all studies but one, due to appropriate forest management. Potential trade-offs between water yield and nitrate loads are addressed in Duncker et al. (2012) and Fan et al. (2016) and between water yield and salt loads in (Nordblom et al., 2010). Nonetheless, despite signals about potential conflicts between water quality and quantity, the economic implications of these trade-offs are rarely examined in the literature.

Promising is the finding that in 8 out of the 11 studies where forest and water relationships were evaluated more broadly in terms of costs and benefits (mainly associated to timber production), forested watershed management is shown to be an economically efficient nature-based solution to supply the watershed services involved. A limited number of studies integrate economic values associated with watershed services into the decision-support method (e.g., Keles and Baskent, 2011; Kucuker and Baskent, 2015; Garcia-Prats et al., 2016; Ovando et al., 2017). These studies show that the internalization of these water values can, in some cases, lead to different optimal forest management decisions than the ones based on the sole maximization of timber revenues. These findings indicate that trade-offs exist between the production of timber and non-timber forest products and watershed services, resulting in benefit losses for the landowner in case no compensation scheme is in place. Generally speaking, an important knowledge gap exists when it comes to the impact of the internalization of competing ecosystem services provision on decision-making related to land use and management.

Although the largest part of the reviewed studies (59%) suggest positive effect of forest-based technologies on the provision of watershed services, it is hard to come to a conclusion with respect to their cost-effectiveness or economic efficiency. Many of the studies (54%) do not provide a clear baseline to examine the additionality of the evaluated forest-based actions. In none of the studies, a comparison is furthermore made between the costs and/or benefits of green, forest-based management action and conventional grey infrastructure for the relevant water services provision.

The results of the *ex-ante* approaches are rather varied. A small number of studies suggest that increasing forest area (Nordblom et al., 2012) or converting natural forest to intensive plantations (Abildtrup and Strange, 2000) will have a negative welfare impact, reducing the provision of watershed services. Some studies suggest that payments for watershed services may generate win-win situations, generating enough incentives for changing current forest management regimes (usually involving thinning) (Garcia-Prats et al., 2016; Susaeta et al., 2017). Other studies show that water payments alone may not fully cover the implementation and opportunity costs of changing current forest management regimes (Ovando et al., 2017, in press).

The three econometric *ex-post* models concur with forest cover having a significant effect on reduced drinking water supply (or treatment) costs (Abildtrup et al., 2013; Fiquepron et al., 2013; Vincent et al., 2016). Nonetheless, it seems desirable to further explore the effect of other variables such as forest fragmentation and other forest attributes (e.g. protective or productive forests, coniferous or broad-leaved forests, mixed or mono-species forests), or the distance of the forested areas to water intake points on water quality levels and consequently on drinking water supply costs.

In conclusion, more research is needed to evaluate the cost-effectiveness and economic efficiency of nature-based solutions to enhance watershed services in comparison to conventional grey infrastructure technologies, typically based on some degree of chemical treatment.

## 4. Discussion and conclusions

This review aimed at analyzing if and how current economic approaches to forest management and water interactions are capturing the complexity involved in ecological, hydrological and economic systems. Our results reveal that the efforts placed on the ecohydrological and economic valuation and evaluation approaches are, in some cases, unbalanced (see Fig. 3). This outcome suggests that the interdisciplinary efforts to address forest and water economic interactions have been limitedly successful. Most studies apply ecohydrological approaches with a low to moderate ability to capture the complexity inherent to forest and water environmental interactions. The economic

valuation and evaluation approaches are furthermore strongly focused on land use and management decisions at the plot or local level. The efficiency of forest management interventions is rarely evaluated with enough rigor and breadth to allow them to be used for a full economic welfare analysis, as the effects of those interventions on the provision of watershed services are often addressed independently of water demand and supply sectors at the local, regional or even national level. Accordingly, we conclude that the integrated analysis of forest and water economic interactions is still in its early stages. Advances made in ecohydrological studies (Vose et al., 2011; Creed and van Noordwijk, 2018), more complex hydro-economic approaches, such as modular or holistic inter-sectoral water allocation models (Brouwer and Hofkes, 2008; Booker et al., 2012), and models handling risks and uncertainty involved in long-term forest management decisions (Hanewinkel et al., 2011; Yousefpour et al., 2012) have not yet reached the forest-hydro-economic domain.

Integrating complex forest and water interactions challenges the estimation of the economy-wide impacts of water and forest policies. Likely changes in climatic conditions, and their impacts on water availability and quality, along with potential changes in the demand for forest goods and services and watershed services, call for the development of more comprehensive and integrated models and methods to guide policy and decision-making. Our review conveyed that current integration efforts have often led to trade-offs in the level of detail by which eco-hydrological and economic systems are represented and described. Forest and water interactions have either been misrepresented through oversimplification in more advanced economic models or vice versa economic impacts have been poorly represented in coupled forestry and hydrology models. Such difficulties and trade-offs are not new in the field of hydro-economic modeling (Brouwer and Hofkes, 2008; Harou et al., 2009), and are partly contingent on divergences in spatial (watershed versus administrative boundaries like province or state) and temporal (daily or seasonal versus annual) scales, and on differences in (narrow) financial versus (broader) economic analysis of the forest management interventions and impacts. Conceiving scientifically sound hydro-economic models to analyze the broader economic welfare impacts of forest management and water use decisions depends, in part, on the scale and scope of the analyzed interventions, as well as on the number of stakeholders and economic sectors involved. However, irrespectively of their scale and scope, methodologies and models are in need of further development and refinement regarding the integration of forest and water interactions, and the representation of economic trade-offs and synergies for broader economic welfare analysis.

There are also additional challenges when aiming to combine detailed ecohydrological processes within comprehensive economic decision-support and evaluation models. Those challenges relate to the limited availability of geo-referenced data and information, including the often complex and confidential nature of cost and price data, and the high data demands of more advanced spatial econometric models. Notwithstanding these data challenges, over the last decade there have been considerable advances in both hydro-economic model design and computational techniques, which have helped to improve the level of detail and accuracy of integrated hydro-economic models (Booker et al., 2012). It is expected that those advances will also favor the interdisciplinary efforts to improve our understanding of forest and water economic interactions.

Most models consider the effect of vegetation cover on the hydrological balance, but the reverse effect of water availability on forest production and yields has rarely been examined (Lauren et al., 2007; Susaeta et al., 2017). This is partly due to the preeminence of empirical forest models used by most studies, which do not allow for addressing forest growth responses to disturbances, such as water constraints. Integrating process-based forest and hydrological models that capture tree and stand growth responses to disturbances is hence the first of the future challenges concerning interdisciplinary research on forest watershed services in a changing environment. Improving the representation of forest and hydrology interactions is expected to be critical for certain climate regions. Integrating water and forest interactions seems critical in arid and semi-arid regions, where more forest cover is expected to reduce downstream water availability (Filoso et al., 2017), at the time water scarcity can affect forest growth, productivity and mortality (Allen et al., 2010). Accounting for climate change uncertainties is also relevant for analyzing the role of forests in regulating streamflow responses to more extreme rainfall events like flooding (Vose et al., 2011). The complex interactions between land use, streamflow regulation, water filtration and climate are still not fully understood (Boholm and Prutzer, 2017).

The economic valuation of forest and watershed services and their connection to economic markets, including supply and demand for the goods and services involved, requires a sound and generally accepted scientific basis, accounting for the relevant spatial and temporal scales, including local and regional (watershed) variability in service provision and site-specific socio-economic context (e.g., Naeem et al., 2015; Wunder et al., 2018). In order to inform sustainable policy and decision-making about payments for ecosystem services, incentive-compatible price setting is needed. These prices have to reflect resource scarcity conditions and opportunity costs, and should therefore be based on economic optimization procedures that allow for the calculation of shadow prices linked to simulations of biophysical forest and watershed services flows. In this way, conventional market prices can be adjusted where necessary for possible distortions, for example due to subsidies or taxes using shadow prices to better reflect the true economic value that forest watershed services provide to society (Turner et al., 2004). Studies that impute values for ecosystem services based on existing information about related values, also referred to as value transfer in the literature (Brouwer, 2000), are surrounded by many uncertainties and potential errors to allow for their reliable use in price setting. Thus, a second research challenge is building an integrated hydro-economic framework to guide optimal forest (and other land uses) and water resources allocation, with a detailed representation of both demand for and supply of forest and watershed services in time and space.

Forest interventions at the small level, such as a plot or a farm, are not expected to affect in a significant way the supply of forest and water-related services. Thus, considering complex multi-sectoral economic interactions at small spatial scales seems unnecessary, contrary to situations where forest interventions take place at a scale at which the provision of water services and their uses are substantially altered over a longer period of time, and accounting for multi-sectoral interactions becomes more critical (e.g., Nordblom et al., 2012). The integration of more detailed eco-hydrological models to simulate forest and water interactions into existing multi-sectoral hydro-economic models will become increasingly important to inform decision-making, especially at larger spatial and temporal scales. This requires that these multi-sectoral economic models are delineated according to the hydrological boundaries of watersheds. Moreover, in order to be able to calibrate and validate these integrated hydro-economic models, they rely crucially on integrated environmental-economic accounting systems, linking economic activities to both market and non-market forest and watershed ecosystem services, for example in a system of satellite accounts around the core System of National Accounts (e.g., Brouwer et al., 2005). Many non-market forest and water-based regulating services are currently underexposed in existing coupled models. Hence, a third challenge is the integration of both priced and unpriced ecosystem values into these hydro-economic modeling attempts (Momblanch et al., 2016), paying special attention to the effects of forest-based actions on the larger set of ecosystem services including regulating and cultural services, which have been systematically ignored in the literature on forest based water services (Ojea et al., 2012).

A fourth and final research challenge is the incorporation of uncertainty into the integrated modeling framework. The identification

and quantification of the sources of uncertainty underlying complex environmental-economic interactions, such as the ones addressed in the studies reviewed in this paper, are often fraught with difficulties, where these uncertainties not only seem to accumulate across the disciplinary domains but also at spatial and temporal scales (e.g. from local to watershed or national scale where interventions upstream may take a while to manifest themselves downstream, and depend on a host of possible influencing factors). A major challenge in this regard is how to account for and quantify the accumulation of different sources of uncertainties in the integrated decision-support tools. This should go beyond the conventional sensitivity and scenario analysis, accounting for input data and structural model uncertainties and making where possible use of ensemble methods and models. Future research efforts have to focus more explicitly on improving our understanding of main contingencies and sensitivities affecting integrated forest and watershed decision models, such as ecological, socio-economic, institutional and climate related risks and uncertainties concerning nature-based solutions.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2018.12.007.

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